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DEVELOPING A FRAMEWORK FOR QUALITATIVE ENGINEERING --  
Research in Design and Analysis of Complex Structural Systems\*

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## PROBLEM DEFINITION AND CORRESPONDING RESEARCH

The research is focused on automating the evaluation of complex structural systems, whether for the design of a new system or the analysis of an existing one, by developing new structural analysis techniques based on qualitative reasoning. The problem is to identify and better understand 1) the requirements for the automation of design and 2) the qualitative reasoning associated with the conceptual development of a complex system. The long-term objective is to develop an integrated design-risk assessment environment for the evaluation of complex structural systems. The scope of this short presentation is to describe the design and cognition components of the research.

Design has received special attention in cognitive science because it is now identified as a problem solving activity that is different from other information processing tasks [1]. Before an attempt can be made to automate design, a thorough understanding of the underlying design theory and methodology is needed, since the design process is, in many cases, multi-disciplinary, complex in size and motivation, and uses various reasoning processes involving different kinds of knowledge in ways which vary from one context to another. The objective is to unify all the various types of knowledge under one framework of cognition.

This presentation focuses on the cognitive science framework that we are using to represent the knowledge aspects associated with the human mind's abstraction abilities and how we apply it to the engineering knowledge and engineering reasoning in design.

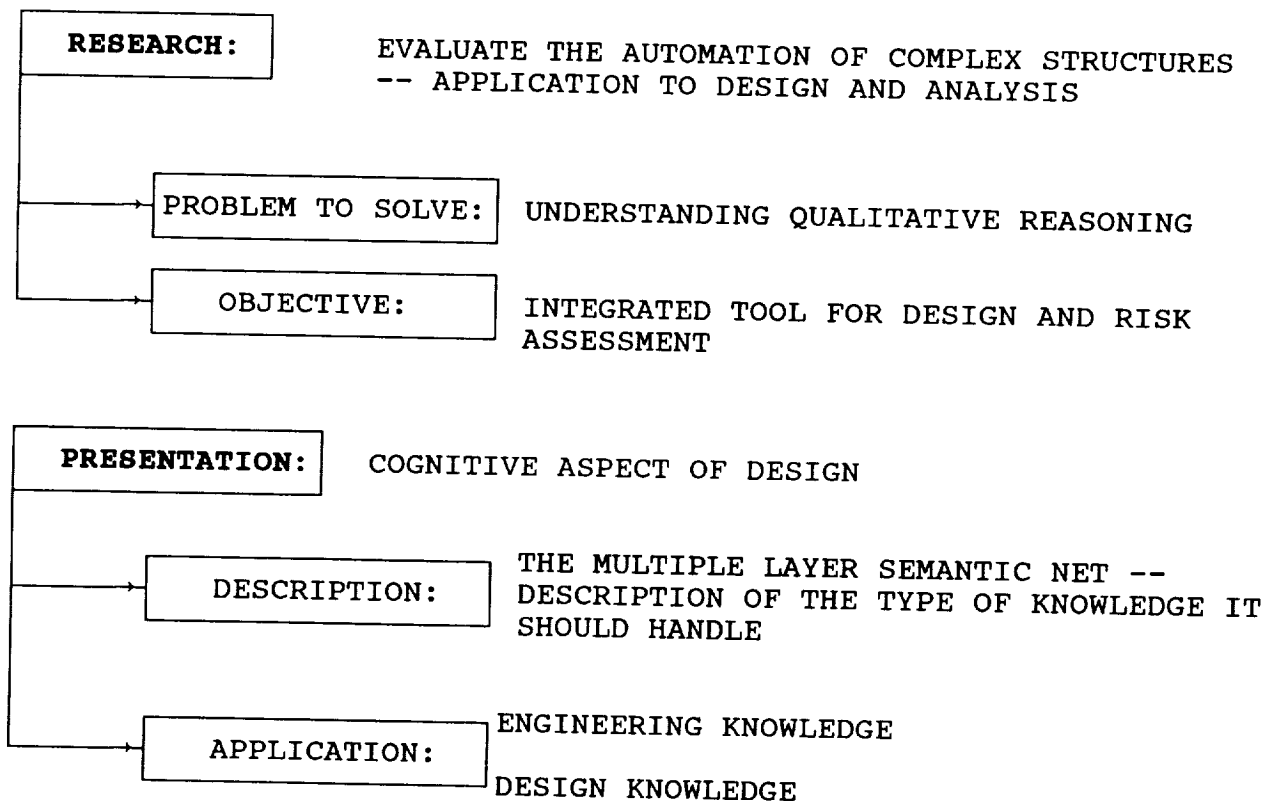


Figure 1

## KNOWLEDGE: PROCESSING OF CONCEPTS

The common denominator among diverse entities such as an overall complex system, a component or a sub-assembly of that system, and the design and evaluation processes themselves, is that they can all be represented by formal concepts which, being associated with the human mind, can fundamentally encapsulate models of the reality that surrounds us [2] (percepts and icons). Concepts are organized in conceptual graphs, semantic nets, and schema or prototypes. Procedures can also be represented in semantic nets [7].

Different design reasoning procedures could be represented in various refinements of the same higher-order semantic net which corresponds, at the highest qualitative level, to deriving the structure for a device such that the device can meet a specific function.

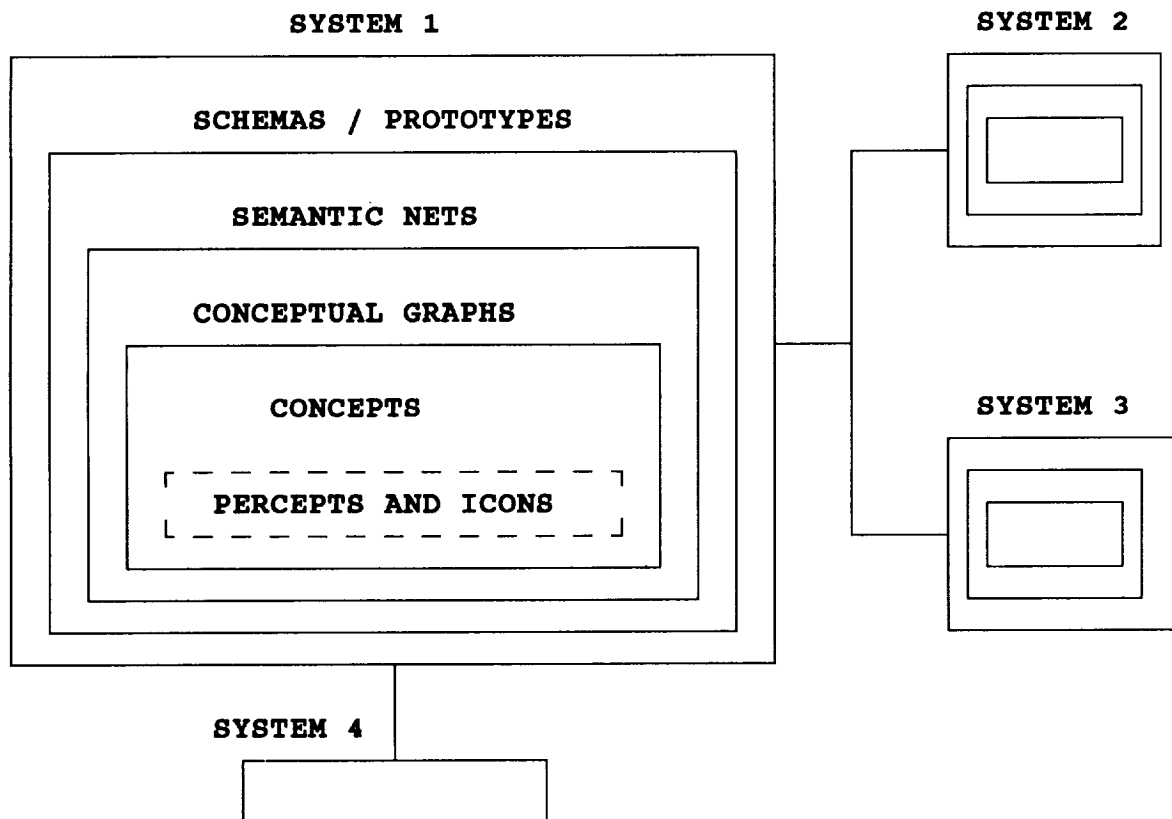


Figure 2

## CONCEPTS AS SEMIOTIC PARADIGMS

Each concept associated with a cognitive process has three fundamental components: A semantic component to describe its function (what it is for), a syntactic component to describe its structure (how it is put together), and a pragmatic component to describe how it relates to its context (what are its behavior and the context in which it is used). Pearson [3] attributes these components to cognitive systems and calls such concepts semiotic paradigms.

The physical symbol system [4] and the connection models [5] have the same components in their paradigms, but vary by the emphasis on the level of representational abstraction at which they are described.

Computer models of a device and the corresponding knowledge can be made at various levels of representational abstraction, but they should always have the three semiotic components so that the knowledge can indeed be described and propagated in a manner similar to the actual cognitive process. This will ensure that the full range of engineering discourse, from the qualitative to the quantitative, will be modeled by computer descriptions.

Furthermore, all three semiotic components are described by both a declarative and a procedural statement. The declarative statement describes "what" is needed in design, and the procedural statement covers "how" to use it.

COMPONENTS OF AN ENGINEERING DEVICE	
LINGUISTIC ASPECTS	ENGINEERING ASPECTS
SEMANTIC	FUNCTION
SYNTACTIC	STRUCTURE
PRAGMATIC	BEHAVIOR CONTEXT

Figure 3

## KNOWLEDGE STRUCTURE

It is our contention that components of knowledge used in processes apparently as different as design and analysis are, in fact, the same. The description of each component and its processing vary as a function of the particular requirements of a problem situation, but the component itself stays the same. We propose that different design / analysis reasoning procedures can, in fact, be represented as different refinements of the same higher-order semantic net. The various levels of detail required to solve problems correspond to various levels of representational abstraction. The same can be said for the representation of the facts in the domain of knowledge: Functional and structural hierarchies of the components of a complex system can be described at various levels of abstraction.

We therefore propose the Multiple Layer Semantic Net (MLSN) [6] as the cognitive knowledge structure which unifies the representation of the various types of knowledge about facts and reasoning. The MLSN is conceptually a layered semantic net. The nets of each layer are isomorphous to one another in that they represent the same engineering concepts, but their descriptions of the concepts are made at different levels of abstraction. The descriptions are qualitative toward the top of the representation and quantitative toward the bottom.

The rest of this presentation describes the cognitive techniques the MLSN should handle and points out the necessity to provide such a unified structure.

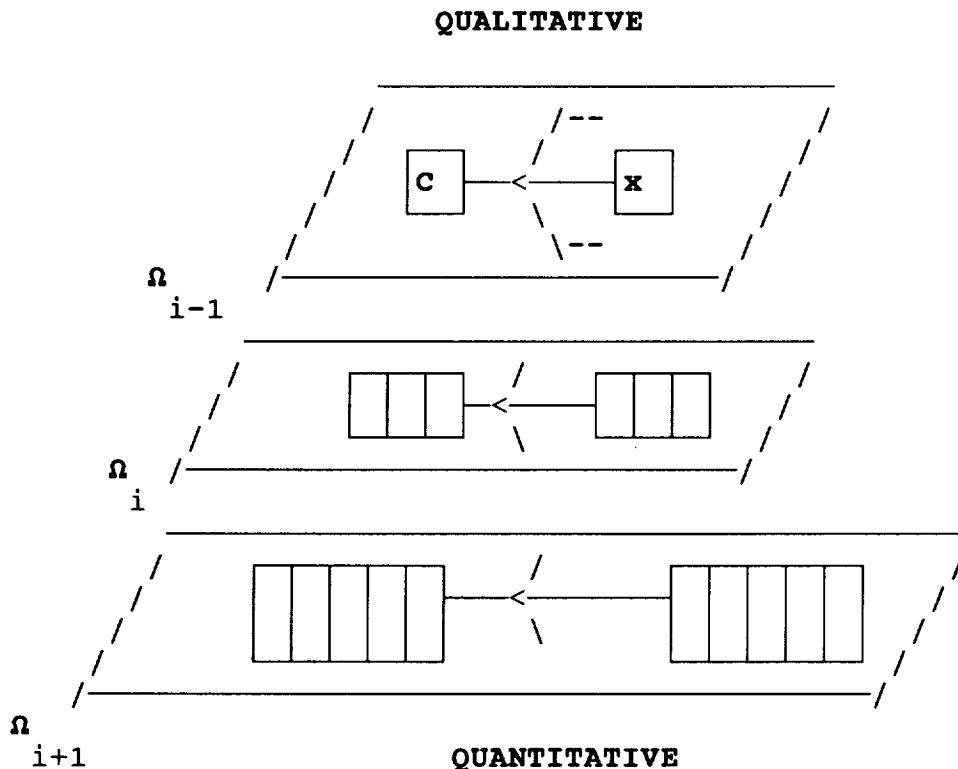


Figure 4

## MULTI-DISCIPLINARY ASPECTS OF THE DOMAIN OF KNOWLEDGE

Most design problems require a combination of knowledge from different domains. For example, in the design of wood structures [7], wood science, wood engineering, and structural engineering are combined. In building design [8], it is architectural, structural, mechanical, and electrical engineering; in aerospace structures [9], aerodynamics, structural engineering, and mechanical engineering. In some design problems, the interaction among the various knowledge domains may be mostly sequential for the larger components of the process, whereas some sub-problems could be solved in parallel [10]. In all cases, a strong interaction exists among the different sources of knowledge, a fact which calls for new approaches such as simultaneous engineering and integrated activities.

The complex structure being designed, e.g., a building, may be decomposed differently in each one of the knowledge domains and may have different function hierarchies in these domains. These various views of the same complex structure can be represented with corresponding hierarchies in the levels of the MLSN. The hierarchies of the different domains are interconnected by the appropriate semantic links, which account for the particular aspects of the context in which the complex structure is used within each discipline. An example is the relationship between the structural decomposition provided by an architect, which becomes the functional decomposition serving as the starting point for design by a structural engineer.

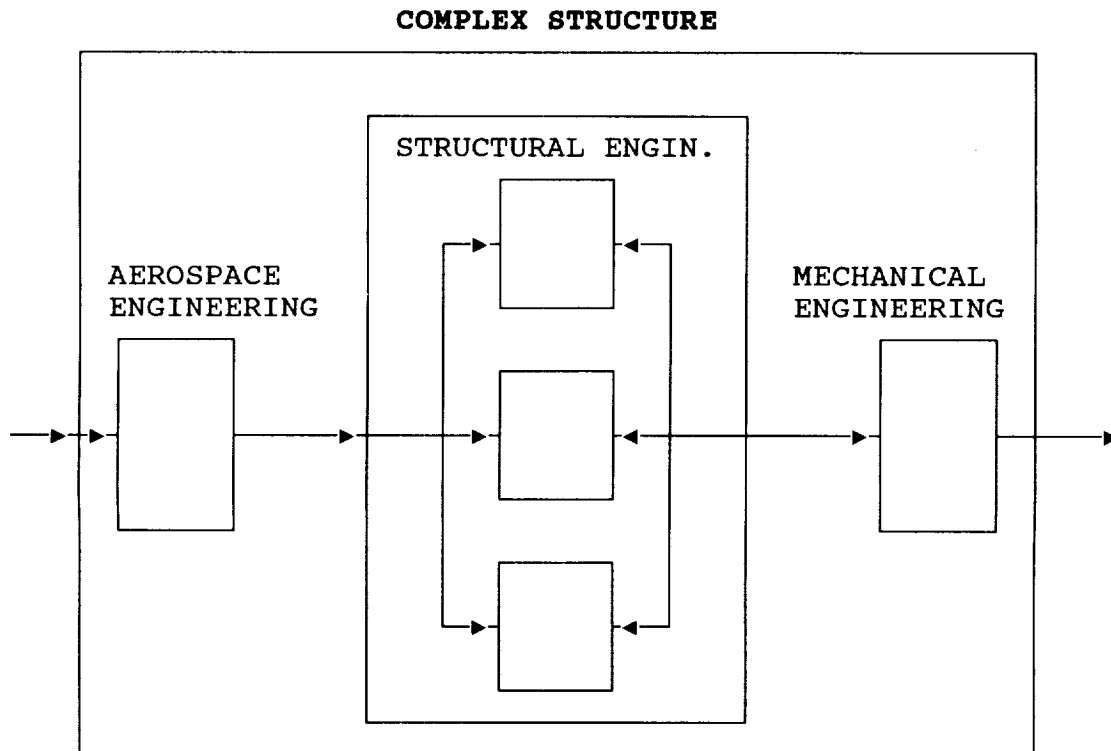


Figure 5

## DECLARATIVE AND PROCEDURAL DEFINITIONS

Two different kinds of knowledge are used to perform a cognitive activity: Declarative knowledge and the procedural knowledge. Declarative knowledge consists of what we know about events, objects, and the relationships between them. Declarative knowledge is also referred to as propositional knowledge and can easily be represented by semantic networks [2, 11]. Procedural knowledge describes how to perform various activities and the dynamic process of how and why operations are performed upon the declarative knowledge.

At a higher conceptual level, declarative and procedural descriptions are part of different knowledge processing skills. According to [12], we first form some declarative knowledge while learning a task; we then correct the declarative knowledge in the associative stage to form some procedural knowledge; in the autonomous stage, these procedures become highly automated. In familiar problems, experts use procedural knowledge in a relatively rapid and automatic fashion [13, 14] and in a new and unusual situation they still have to rely on their declarative knowledge.

Hence we propose that procedural knowledge is used for routine designs [15], declarative knowledge is used for creative and innovative designs, and a combination of both is used for design by redesign [16].

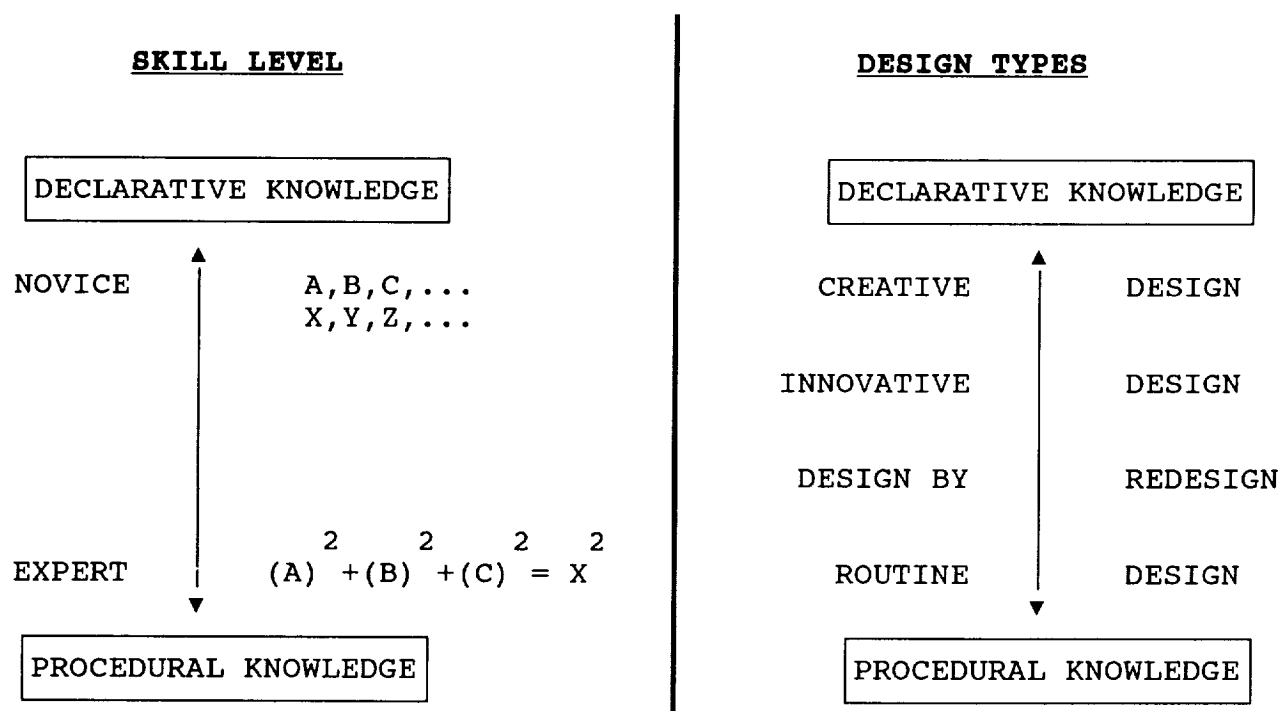


Figure 6

## FROM QUALITATIVE TO QUANTITATIVE, COMPLETE OR PARTIAL ENVISIONMENT

The human mind can envision a complex system in its entirety or zero-in on one part of it. In doing so, it switches from higher levels of abstraction where the information tends to be more qualitative to lower levels of abstraction where it is more quantitative [6]. This is exemplified in the decompositional stage of design in which one critical component or sub-system is designed in more detail with the assumption that it will later fit with the rest.

Just as the human mind shifts from qualitative to quantitative descriptions, so does the design process. A design at a deeper level of description defines one at a higher level by providing more detail about the components. This characterization corresponds to the cognitive process of definition (the reverse of abstraction). It can also describe the reasons for having to define more precisely the concepts parametric in nature and includes the procedures to do so.

Modeling the design knowledge in multiple layers is especially appropriate in routine design [15]: The structures being designed and their components stay fundamentally the same from one application to the next. Only the numerical values of the parameters change from one specialization to another. It is therefore not necessary to abstract toward the generalized conceptual structure, design after design. This process corresponds to moving from one level upward, then back down in the MLSN in a fundamentally qualitative-then-quantitative process.

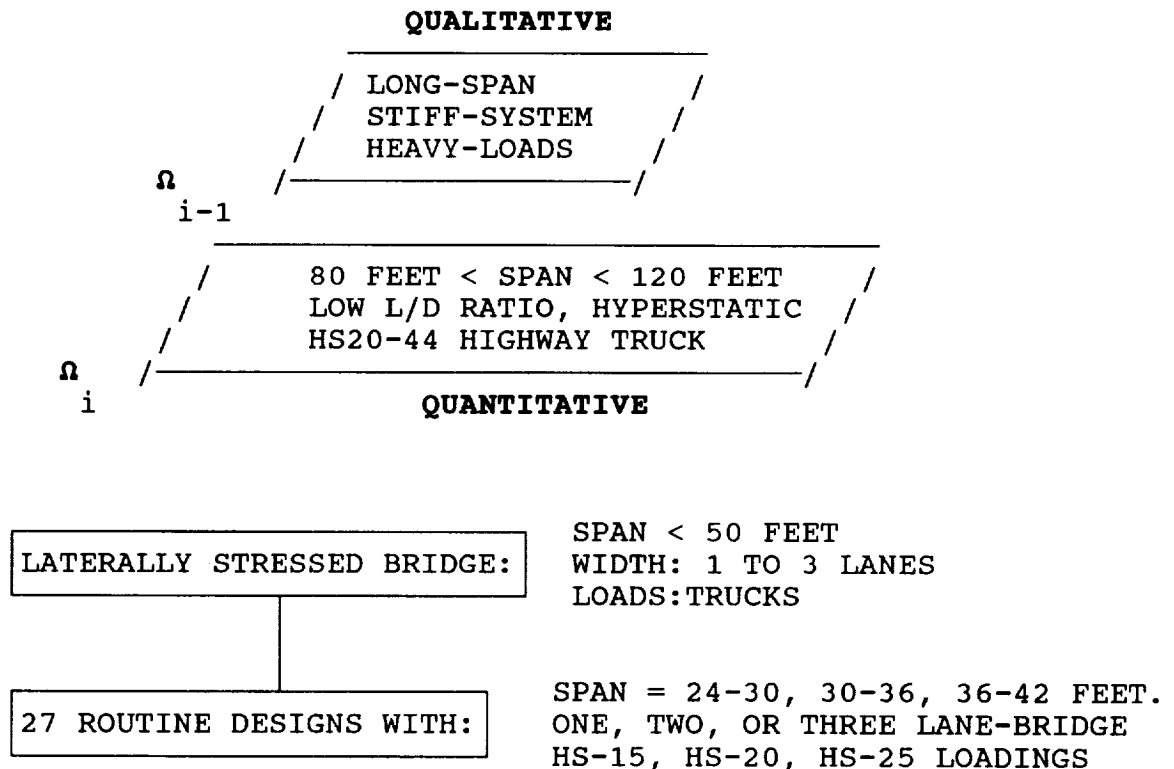


Figure 7



## **SIMULATION: DESIGN AND EVALUATION**

The procedures of design and evaluation are dual of one another in the following sense: Design consists of creating the structure of a device that exhibits a specific and desired behavior or that is meant to serve an intended purpose. Evaluation, on the other hand, consists of analyzing the behavior of a device in an effort to understand what its structure must be for it to exhibit that behavior. Both design and evaluation processes use the same knowledge base of facts and relations; only the manipulations of the components vary between the processes, as will be shown later.

Design and evaluation can be viewed as two refinements of the concept of simulation. Simulation is the attempt to make the composition of a system exhibit a certain behavior, and depends on the ability to create the system in the first place, whether it is a preliminary design alternative or a model of an existing system.

Because of their duality and generalization to the same concept, it is logical to integrate a design and a risk assessment into the same program: The structure of a complex system is established to some degree of completeness during a preliminary design. That structure can then be investigated to evaluate the risk associated with a potential failure of some of the components of the structure. The decision to accept or reject the preliminary design alternative is then made based on the results of the risk analysis.

**DESIGN:** BEHAVIOR OR FUNCTION  $\Rightarrow$  STRUCTURE

**EVALUATION:** STRUCTURE  $\Rightarrow$  BEHAVIOR AND/OR FUNCTION

**$\therefore$  DESIGN AND EVALUATION ARE DUAL ON A SEMIOTIC BASIS**

**CONSEQUENCES:** . GENERALIZATION OF BOTH TO SIMULATION

. INTEGRATION OF PRELIMINARY DESIGN AND  
RISK ASSESSMENT

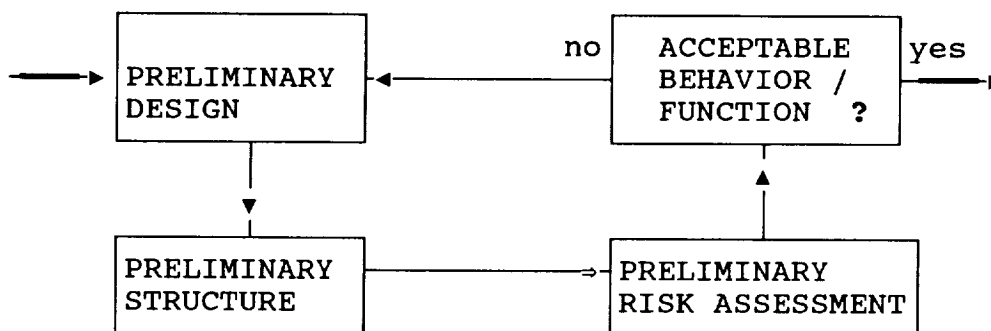


Figure 8

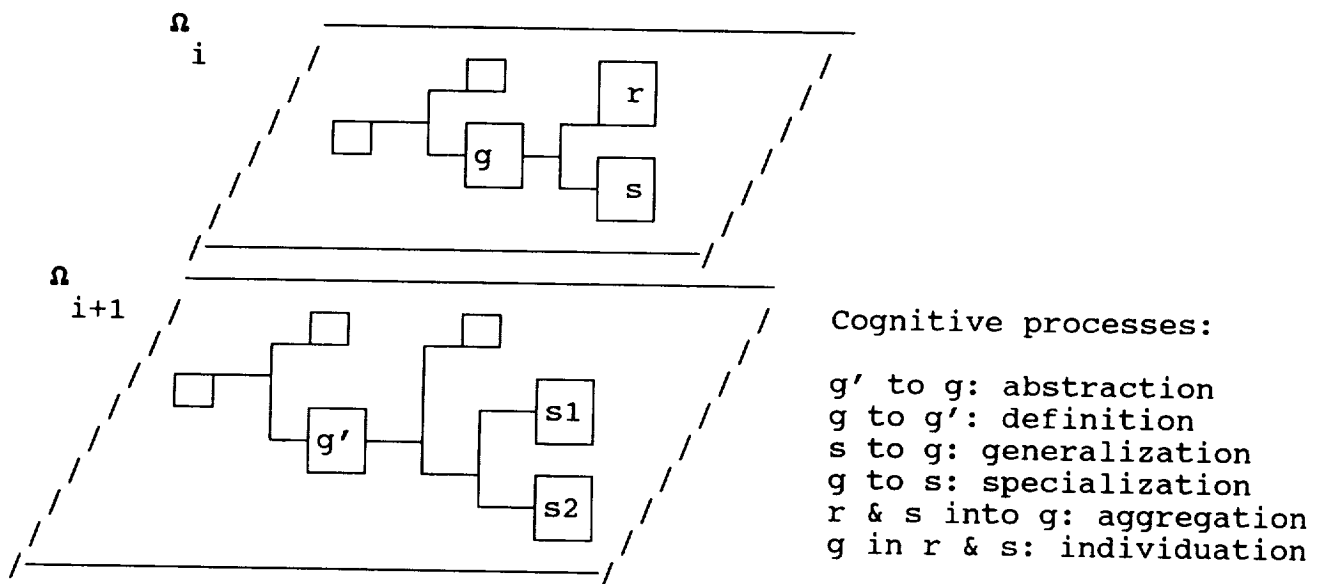
## FUNDAMENTAL DESIGN STRATEGIES AND THEIR COGNITIVE EQUIVALENTS

Every design involves four steps: Problem formulation, conceptual design, embodiment design, and final design. The first step of the conceptual design establishes the functional decomposition of a complex system and its components. This decomposition corresponds to the cognitive processes of 1) specialization of a concept into an instance, and 2) individuation of the concept into sub-components.

The second step of the conceptual design is the design synthesis. This assembles some components into a more complex structural hierarchy which corresponds to the earlier functional decomposition. The corresponding cognitive process is the aggregation of concepts.

Some basic design strategies applicable during the conceptual design are the routine design, design by redesign, innovative design, and creative design. Any combination of these can lead to even more complex strategies.

Design by redesign first generalizes a concept to a higher-order class-concept and then specializes to another instance. Routine design first abstracts to a more qualitative model of the same structure and redefines it into another more quantitative model. Both processes are sketched on the MLSN below. As already mentioned, procedural knowledge is used in routine design, declarative knowledge in creative design, and a combination of both in innovative design and design by redesign.



Design strategies and the MLSN:

- . Routine design: path from  $s1$  up to  $s$ , then down to  $s2$
- . Design by redesign: path  $s1$  to  $g'$ , then to  $s2$

Figure 9

## DESIGN PROCEDURES AND THE SEMIOTIC RELATIONSHIPS

The reasoning procedures of the design problem solving process the knowledge among the components of a semiotic device, either by deriving one semiotic component from another inside one device, or by comparing similar components between two devices. There are six possible relationships among the three semiotic components of a device, all used either in design or analysis.

The FUNCTION-to-STRUCTURE mapping (i.e., deriving the structure from the function) and the BEHAVIOR-to-STRUCTURE mapping take place in the design synthesis. They use teleological reasoning. The STRUCTURE-to-FUNCTION and the STRUCTURE-to-BEHAVIOR mappings are analysis processes. They use causal reasoning.

Except for the mapping from structure to behavior, all mappings are of the type one to many. For example, several functions can be met by one structure, just as multiple structures could serve one function. A given structure can only generate one behavior at a time, with a fixed context.

The FUNCTION-to-BEHAVIOR mapping can be part of the innovative design which consists of finding new applications to an existing device. This mapping can be one to many. Finally, the BEHAVIOR-to-FUNCTION mapping corresponds to a qualitative analysis process and is a one to one mapping if considered in one context.

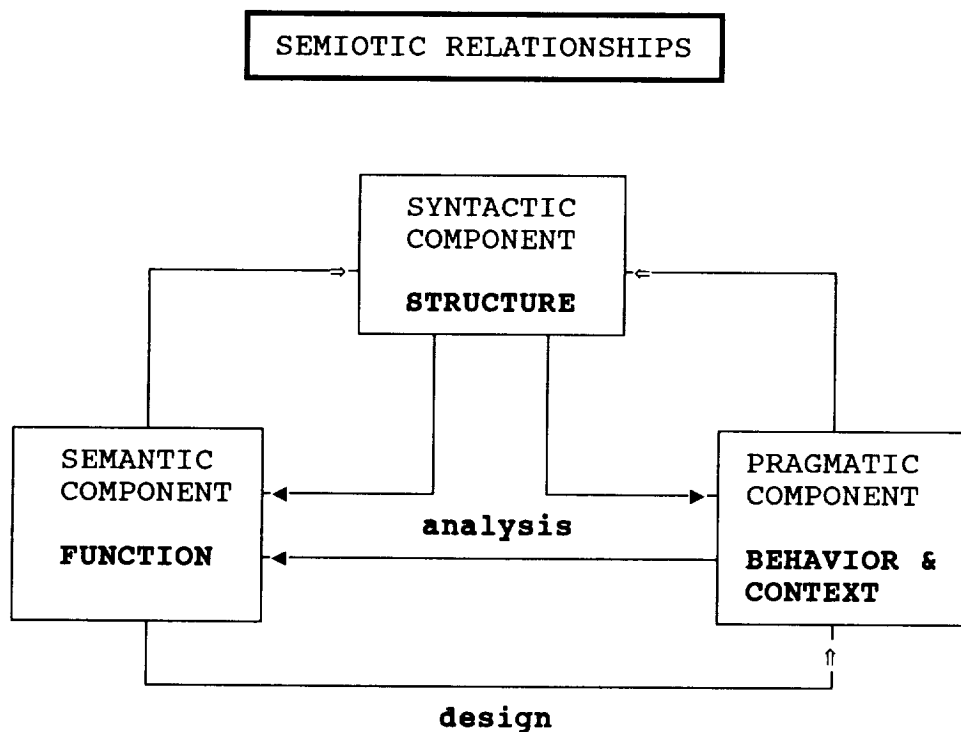


Figure 10

## DESIGN STRATEGIES AND THE SEMIOTIC RELATIONSHIPS

The design process is based at the fundamental level on causal and teleological reasoning. Causal reasoning processes "what it is" in order to derive "what it does". It is applied, for example, in a backward chaining manner in the FUNCTION-TO-BEHAVIOR mapping of an innovative design where a new usage is identified for a device. Teleological reasoning, by contrast, processes "what it is for" to derive "what it should be". It is applied, for example, in the traditional derivation of the STRUCTURE from the FUNCTION.

At a higher level, some design strategies are Design by analogy, which compares corresponding components of different devices; design by constraint satisfaction, which builds up information requirements from the context for the function and structure of a device; and design by analysis, as in the innovative design process mentioned above. In case-based designs as in design by analogy, all transformations could be used [17].

Even higher order design strategies still manipulate the semiotic components. Routine design involves transformations of a structure from one instance into another one. Design by redesign involves iterations on the transformations between the function and/or the behavior and the structure. In all multidisciplinary designs, structures of one domain are functions for another. Through the design process, the structures of the second domain finish completing the description of the initial structures.

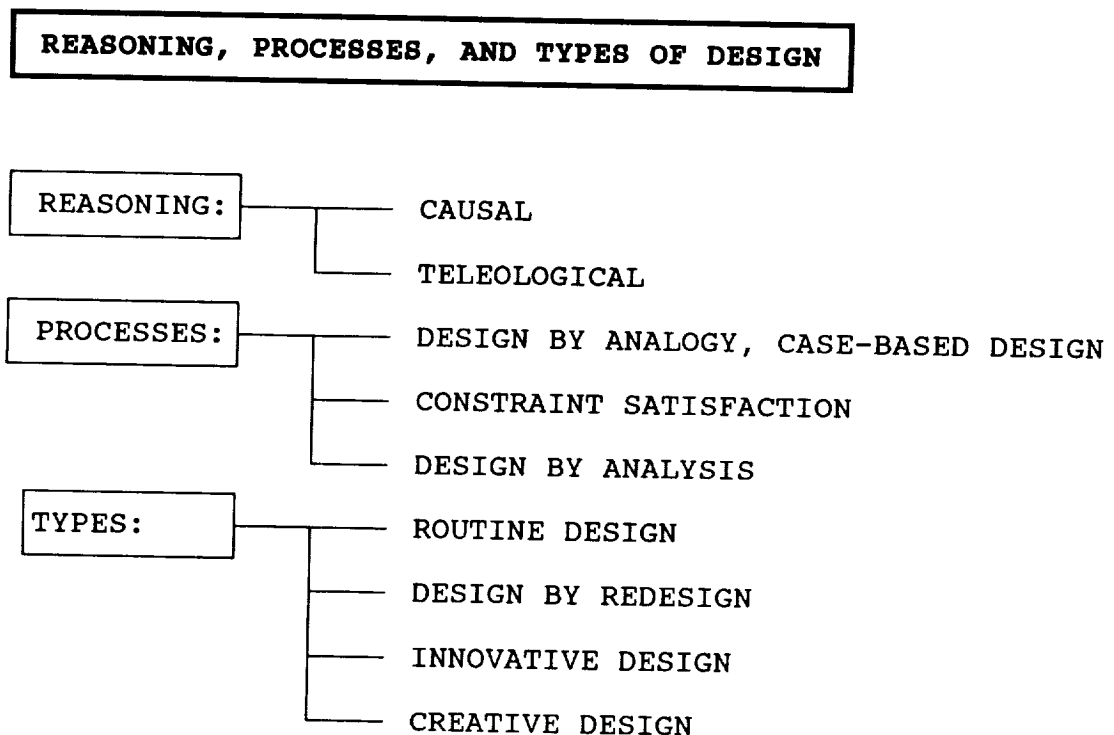


Figure 11

## SUMMARY

The research in automating the design and evaluation of complex systems led to the formulation of a cognitive knowledge structure developed to facilitate the acquisition and representation of knowledge at multiple levels of abstraction.

The knowledge structure, the multiple layer semantic nets (MLSN), consists of isomorphous semantic nets describing the relationships among concepts viewed as semiotic paradigms. The components of the semiotic paradigms (structure, function, behavior and context) are described from qualitative levels to quantitative levels by both declarative and procedural descriptions.

The MLSN was described here in the perspective of the design process and the design strategies it should handle. It is also applied in another component of the research to investigate and develop techniques, based on qualitative reasoning, to evaluate complex systems.

The MLSN is now used to guide the development of a computer program which will perform both the design and the risk assessment for complex structural systems.

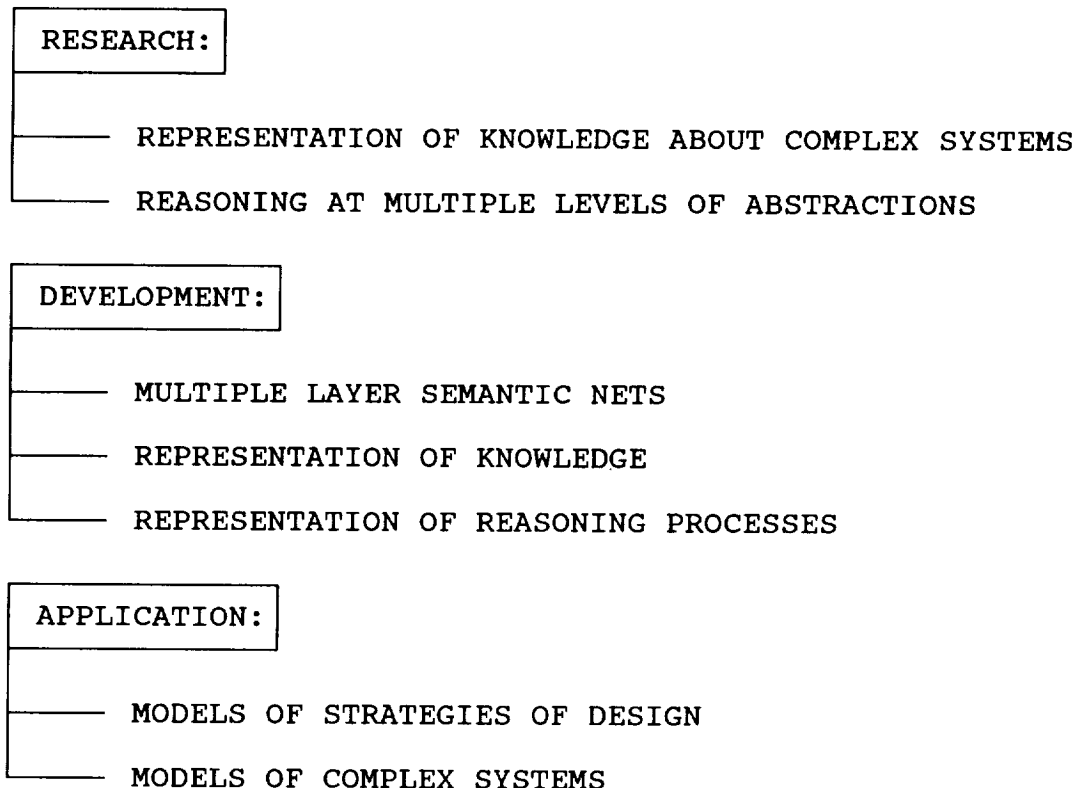


Figure 12

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